

# **Wave Transformation and Setup from a Cross-shore Array of Acoustic Doppler Profilers (Poster)**

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## **Introduction**

The US Army Corps of Engineers developed a cross-shore wave and current array at the Field Research Facility (FRF) in Duck, NC to collect real-time directional wave data for investigating wave energy transformation and evaluating numerical wave model performance (Hanson et al. 2009a). The array consists of a scanning beach laser, nearshore pressure gages, acoustic current profilers through the surf zone, a pier-based meteorological station and offshore wave buoys. Custom spectral processing routines have been developed for the acoustic profilers and resulting directional wave estimates were validated at the 8-m depth station with the co-located FRF 8-m high-resolution directional array of bottom mounted pressure sensors. A wide variety of wave events observed between December 2007 and August 2011 were extracted for use by the National Oceanographic Partnership Program (NOPP) Waves project. The selected events consist of pure swell, pure wind sea, mixed seas, and assorted wind conditions including high and low wind speeds directed onshore and offshore.

The nearshore portion of the array is within the field of view of a 43-m high ARGUS camera station that provides high-resolution images of surf zone behavior and regions of wave dissipation (Holman and Stanley 2007). This ARGUS data was used to investigate AST signal degradation due to wave breaking and the effect that has on wave height measurements and quality control of spectral estimates.

## **Cross-Shelf Wave and Current Array**

The USACE array was installed so it aligned with NOAA's NDBC station (44014) near the shelf break in 46m depth, covering 95 km of the continental shelf. A Riegl scanning laser was added in August 2011 to measure runup, setup, and surf-zone waves. The laser is mounted on the dune crest approximately 30m from the shoreline and has a range of about 100m, overlapping the shoreward-most pressure wave gauge (Figure 1). The 8m-AWAC is co-located with the FRF 8-m high-resolution directional array of 15 bottom mounted pressure sensors (Figure 2), termed the 8m Array, and provides ground truth to the AWAC data. Two Paroscientific pressure gauges ("Paros") were added in nominal depths of 1 and 2 m in August 2011. These Paros sensors were buried to reduce the Bernoulli effect of pressure drop due to currents moving past the gauge orifice, which improved the accuracy of water level measurements.

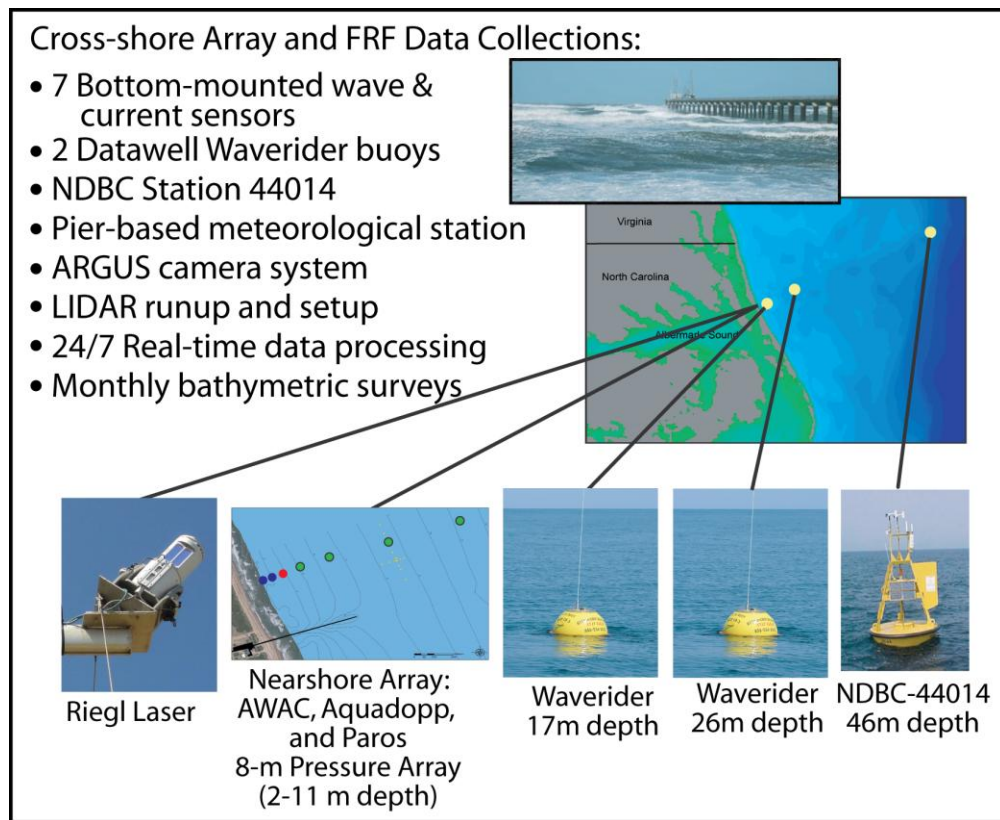


Figure 1. Cross-Shore Wave Array and beach laser scanner.

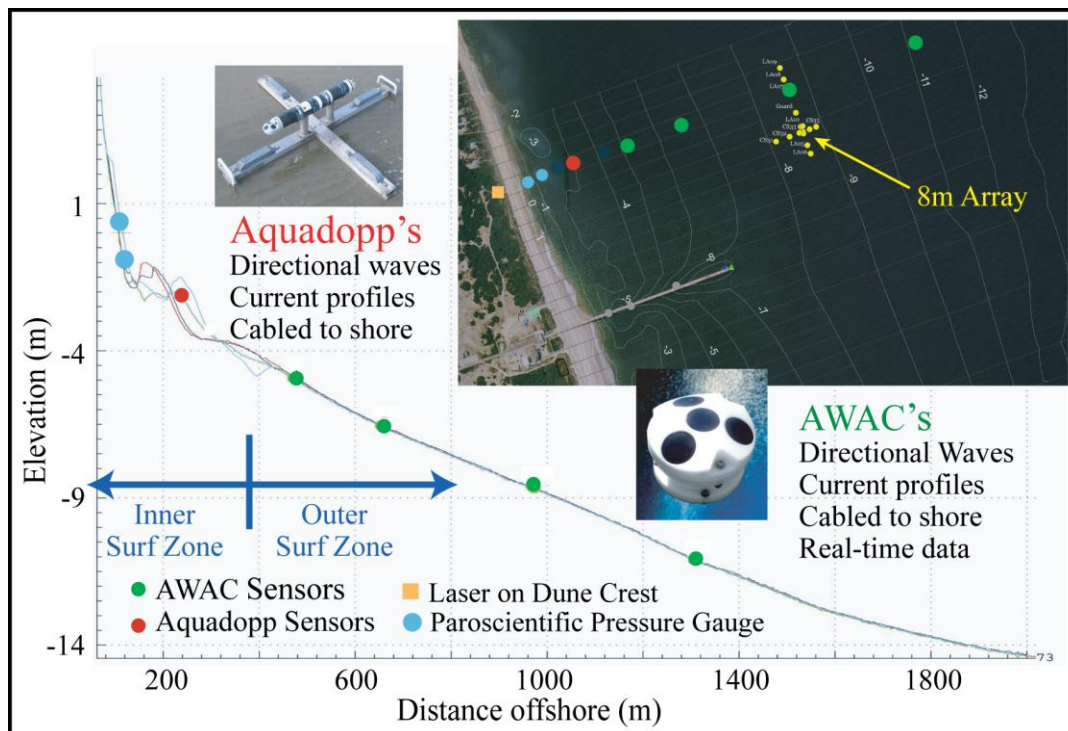


Figure 2. Surf zone inner-array of AWAC, Aquadopp, and Paros pressure gauges.

## Real-Time Data Collection and Analysis

The 8m-Array is a phased array of pressure sensors with dimensions of 120m cross-shore and 255m alongshore. The array design was based on the work of Davis and Regier (1977) and uses the Iterative Maximum Likelihood Method (IMLM) for the wave analysis (Pawka, 1983). A detailed explanation of the array and analysis method can be found in Long and Oltman-Shay (1991). Directional wave spectra from the array are used for verification of the AWAC spectral analysis.

Data from the Datawell Waverider buoys are acquired through HF and Iridium communications. Buoy spectra are computed hourly using the method of Longuet-Higgins et al. (1963) for obtaining directional coefficients and full direction spectra are computed with IMLM analysis.

Four Nortek AWACs were installed in December 2007 with cabling to shore for real-time data acquisition and powering the instruments. Spectra are computed using an IMLM with a combination of the acoustic surface tracking beam (AST), the individual velocity beams, and pressure sensor data.

AWACs have 4 beams; one vertical and three slanted at 25°. The vertical beam is an Acoustic Surface Tracking (AST) signal that samples at 4 Hz, twice that of the oblique beams, and provides measurements of surface displacement. A spectral reconstruction technique was developed that uses a combination of wave analysis methods. The lower frequency end of the spectrum uses IMLE processing of the orbital currents computed from the three oblique beams and the AST (SUV method: S=surface track, UV=horizontal orthogonal current), which is treated as a point measurement. The upper end of the spectrum uses IMLE processing with the AST and individual radial-velocity beams as a spatial array (Array method). If the AST signal fails quality checks the pressure (P) signal is substituted for the AST (PUV method).

Cutoff frequencies are computed based on the horizontal separation of the velocity beams ( $L$ ) and wavelength ( $\lambda$ ). The SUV method is exclusively used at frequencies below which  $\lambda = 10L$ , and the array method is exclusive at frequencies above  $\lambda = 6L$ . Between these frequencies a linear combination of the two spectra are used. A maximum frequency ( $f_{max}$ ) cutoff is set at the lesser frequency of when the wavelength is two lag distances ( $\lambda = 2L$ ), becoming spatially aliased, or when linear wave theory wave pressure attenuation is 0.1 and PUV method is used.

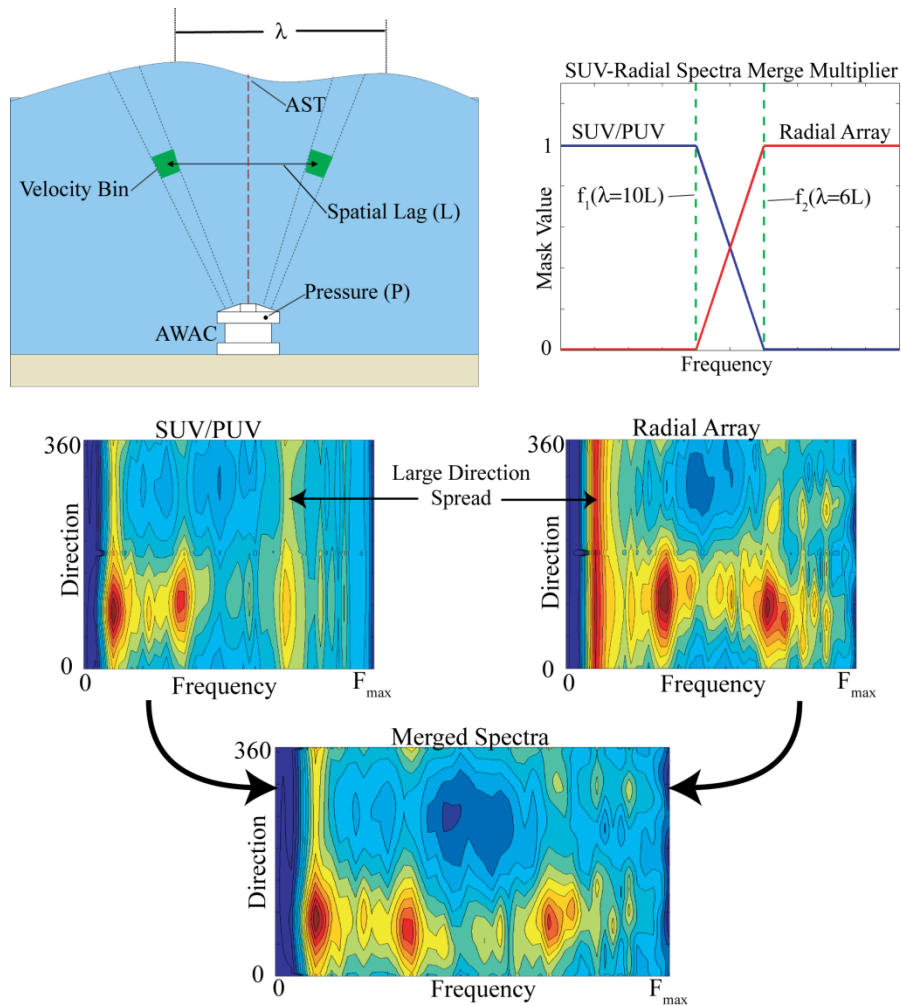


Figure 3. SUV/PUV and radial spectra merge method.

## Spectra Merge Method Validation

Significant wave height, peak period, and peak direction statistics were computed from merged 8m-AWAC spectra (Figure 4, dashed line) and compared with results from the co-located 8m-array (solid line). The Interactive Model Evaluation and Diagnostics System (IMEDS) was used to compute biases, RMS errors, and scatter indices (SI) for October 2009. Results are provided in Table 1. Excellent agreement of wave statistics was observed, validating the use of the merged spectra.

**Table 1. IMEDS Validation Summary of 8m Array and 8m AWAC.**

October 2009 Validation Errors			
	Bias	$E_{RMS}$	SI
Height (m)	0.01	0.09	0.07
Period (s)	-0.18	0.98	0.11
Direction (deg)	4.0	---	---

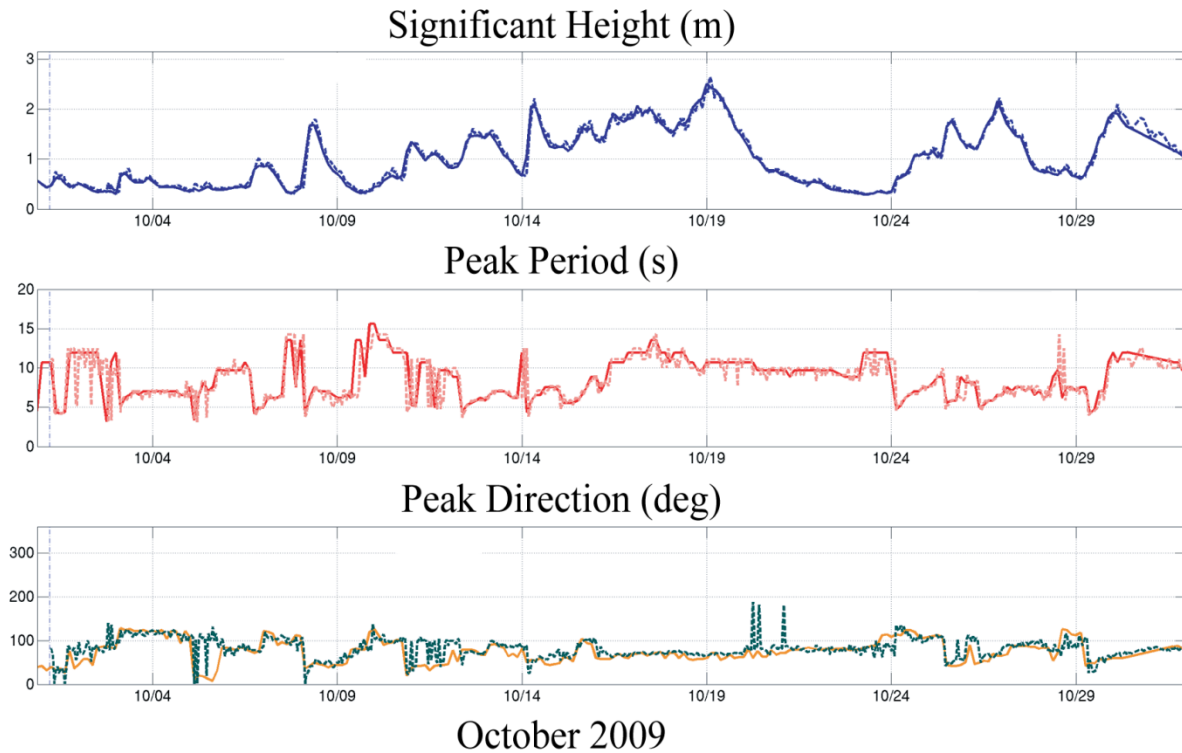


Figure 4. Validation of 8m-AWAC merged spectra results with 8m-Array.

## Wave Transformation

Hurricane Irene was the most recent storm event that peaked at the FRF on 27 Aug 2011, with wave heights reaching 5.8m at the 17m Waverider and sustained winds of 32.6 m/s. An over-plot of wave heights for the entire array appears in the top panel of Figure 5. The middle panel shows the wave energy transformation measured across the array near the storm peak. A preliminary estimate of wave setup over the inner-array, between 11m and 1.5m depths, was 0.27m (bottom panel). Since the Paros gauges are buried, the mean pressure offset from currents (Bernoulli effect) is assumed negligible. The Aquadopp and AWAC gauges are mounted above the bottom, thus potentially measuring biased mean water levels due to currents.

To improve AWAC water level estimates, an empirical approach will be taken that correlates measured current velocity and mean pressure offsets relative to the AST. The AST measurement tracks the water surface well in non-breaking waves but tracks poorly when there are entrained bubbles from breaking. This was the case during Hurricane Irene where Argus images verified wave dissipation (breaking) across the inner-array, requiring that pressure be used for water level estimation. Water levels from the shoreward-most sensor measured setup slightly lower than the sensor 30m seaward. The decrease in setup at the shoreward gauge was not expected. We assumed the gauge became un-buried, the pressure orifice was exposed to the currents, and a dynamic pressure drop was experienced. A post-storm bathymetric survey determined the depth increased at that location, possibly putting the gauge

0.2m above the bottom. The sensor 30m seaward sensor (Paros-2m) has a co-located altimeter tracking the bottom location that indicated it stayed buried.

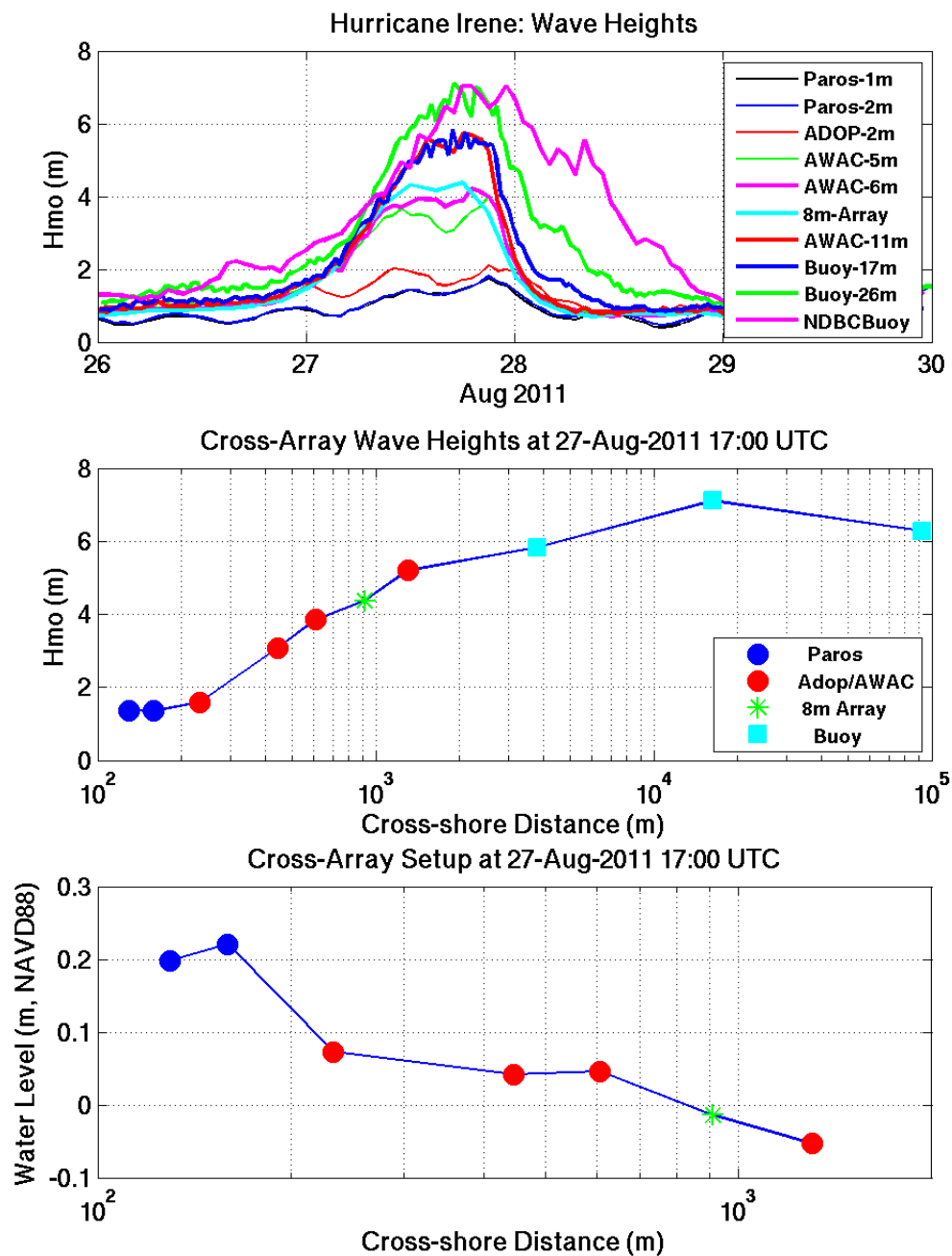


Figure 5. Preliminary wave data from Hurricane Irene (August 2011).

Two additional Argus cameras were added to the existing 7-camera Argus system in September 2010, specifically for observations over the inner-array. These new cameras have a view through a spinning-

window, as used on a ships helm, which displaces water and provides clear images during rain. Several types of images are obtained (e.g., snap-shot, variance, time-average, lightest and darkest pixels), with wave dissipation and initiation of wave breaking being easily recognized in the brightest-pixel images. An example storm image in Figure 6 shows wave breaking beginning at the 8m AWAC where the white pixels indicate wave dissipation. Other camera views verified breaking continued shoreward of the 8m AWAC, corresponding to the decrease in wave heights.

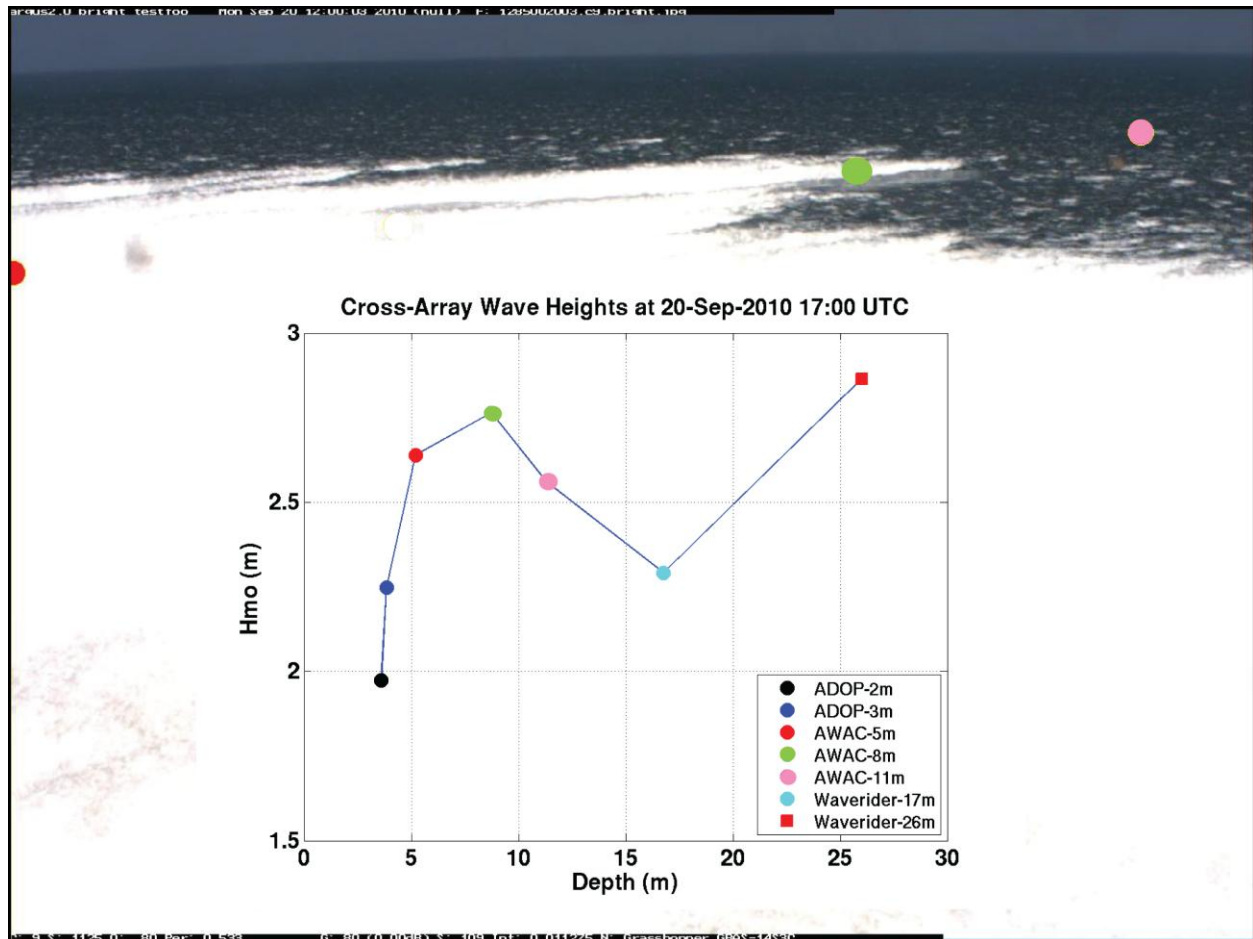


Figure 6. Argus image (brightest pixel) with 5m (red dot, 8m (green dot), and 11m (pink dot) AWAC locations and cross-shore wave heights. Wave breaking begins at the 8m AWAC (green dot).

The dune-mounted laser made high quality measurements of wave runup, setup, and foreshore changes through several storm events. This appears to be an excellent method for making these measurements, with the main limitations being rain and shadowing behind waves at the farthest ranges. Nevertheless, the initial measurements have provided excellent data with high temporal and spatial (across-shore) sampling. The shoreward most pressure sensor is within the range of the laser and preliminary comparisons have shown good agreement, an example is shown in Figure 7.



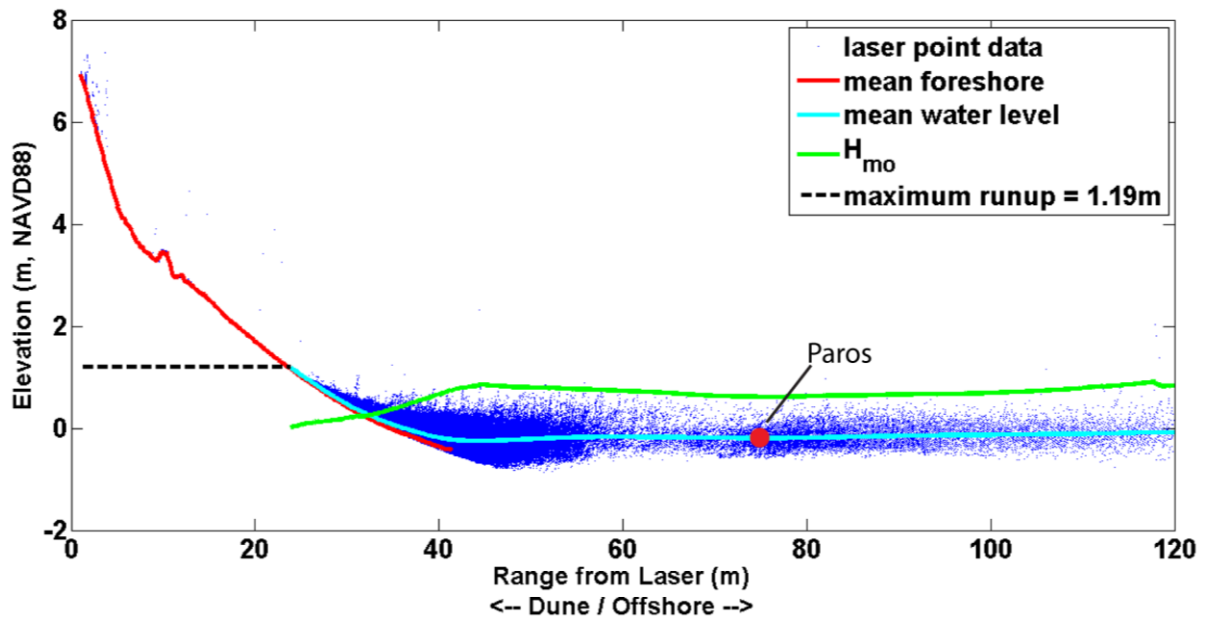


Figure 7. Example cross-shore laser scan (blue dots) with  $H_{mo}$ , setup, and runup. The nearshore pressure sensor water level (red dot) plotted for the same time period.

## NOPP Data Archive

The array data are being used for source term improvements and model validation by NOPP Waves Program. To identify events, directional wave spectra are processed through frequency-direction partitioning routines that identify sea and swell waves. Data mining tools were developed that use this partitioned data to identify and extract critical events for model validations; 12 of these events have been extracted and provided to NOPP partners. Events were selected to provide different wind and wave conditions, including pure wind sea, pure swell, mixed seas, and light onshore or offshore winds. Significant wave heights for these events, measured at the 17m Waverider buoy, ranged from 0.7 to 5.8m with peak wave periods ranging from 3 to 17.3 s. Supporting bathymetric data, currents, and Argus imagery are also included in the event archives. A summary of these datasets is presented in Table 2.



**Table 2. Cross-Shore Array Wave Events Provided to Waves NOPP Project.**

NOPP Wave Events							
FRF Cross-Shore Array - 17m Waverider Station							
			Winds		Waves		
Date			U10	TWD			
Event	Type	yyyy-mm-dd	(m/s)	(From N)	Hs (m)	Tp (s)	Description
E1	Hurricane Earl	2010-09-03	24.0	4.0	4.5	8.5/15	Mixed sea and swell
E2	Hurricane Bill	2009-08-22	4.0	326.0	3.6	17.3	Swell with harmonics; highly nonlinear
E3	Noreaster Ida	2009-11-13	14.9	48.0	5.2	12.9	Wind sea event
E4	Noreaster	2008-10-19	16.5	24.0	3.7	9-12	Wind sea event
E5	Noreaster	2008-09-25	18.2	69.9	4.9	12.5	Wind sea event
E6	Swell	2009-03-26	6.6	189.0	3.1	15.2	Swell, steady
E7	Swell	2009-08-29	5.0	variable	1.6	8-14	Swell, light winds
E8	Swell	2010-08-29	1.2	167.0	1.9	13.7	Swell
E9	Windsea	2009-12-19	12.0	ENE	4.3	10-11	Wind sea event, shore parallel
E10	TS Hanna	2008-09-06	13.5	SE	2.8	7-12.5	Developing windsea over swell
E11	Fetch Limited	2010-02-26	12.0	W	0.7	3.0	Offshore winds, small opposing swell
E12	Hurricane Irene	2011-08-27	32.5	E-W	5.8	13-15	Onshore wind rotates to offshore

## Summary

The FRF has established and maintained a unique coastal array of wave and current gauges for capturing world-class datasets of wave transformation across the continental shelf and through the surf zone. Key accomplishments and findings for the current study are:

- A custom data processing approach was developed for the AWAC's that combined both orbital and radial velocity spectra to improve (decrease) directional spreading of the spectra.
- Comparisons with the FRF 8-m pressure array confirmed that the AWAC system accurately captures the bulk characteristics of the evolving directional wave field.
- An archive of 12 events has been provided to the NOPP waves team, with more to be added, for improvement of source term research and evaluation of numerical wave model performance. These data sets demonstrate that the array captures all phases of wave transformation from shelf to shore.
- Preliminary estimates of wave setup from cross-shore water levels during Hurricane Irene were as much as 0.27m from 11m depth to the shore. These estimates will be examined in greater detail, possibly adjusting Aquadopp and AWAC water levels with current-corrected offsets and AST data, and then comparing with setup estimated from measured radiation stresses.
- Additional setup measurements from pressure sensors will be validated with laser-scan measured setup, providing quality assurance to the data.

## References

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## Acknowledgments

The authors would like to thank Mr. Richard Slocum, Dr. Kate Brodie, and Dr. Jesse McNinch for their laser data. Thanks to Ms. Eve Devaliere for her contributions to the IMEDS and XSHORE data analysis packages, and Mr. Philip Balitsky for developing an early version of XSHORE. The FRF personnel (Ray Townsend, Brian Scarborough, Jason Pipes, and Dan Freer) were vital to the AWAC and buoy deployments. This project was made possible thanks to funding from the U.S. Army Corps of Engineers FRF Measurements and MORPHOS programs, the Office of Naval Research (NOPP).